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A photon-counting photodiode array detector for far ultraviolet (FUV) astronomy

G. F. Hartig, H. W. Moos, R. Pembroke and C. Bowers

Physics Department, Johns Hopkins University
Baltimore, Maryland 21218

Abstract

We have developed a compact, stable, single-stage intensified photodiode array detector for photon-counting, far ultraviolet astronomy applications. The intensifier, constructed by ITT, employs a saturable, 'C'-type MCP (Galileo S. MCP 25-25) to produce high gain ($\sim 10^6$) pulses with a narrowly peaked pulse height distribution. A high efficiency, opaque CsI photocathode is coated directly onto the MCP input surface. The P-20 output phosphor exhibits a very short ($\sim 10\mu s$) decay time, due to the high current density of the electron pulses. We are currently coupling this intensifier to a Reticon RL1024-SF self-scanning linear photodiode array, with 1024 - 25μ x 2.5 mm tall diodes. This device has a fiber optic input window which allows direct, rigid mechanical coupling with minimal light loss. Initial testing has been accomplished using the driver circuitry supplied by Reticon, followed by a 4 bit ADC and DMA interface with an HP 9845 desktop computer. The array was scanned at a 250 KHz pixel rate. The detector exhibits more than adequate signal-to-noise ratio for pulse counting and event location. Event location algorithms that compute the pulse centroids to 1/2 diode width accuracy have yielded detector spatial resolution limited by the MCP channel spacing (32μ). Designs for a fast amplifier/clock driver circuit and a bit-slice microprocessor device for real-time photon event location are now being implemented. We anticipate that the short phosphor decay time and use of a fast, dedicated microprocessor for event location will permit rapid scan speeds and hence large dynamic range. The small physical size, stability, insensitivity to environment, low bias voltage, wide dynamic range and independent pixel properties combine to make this detector very suitable for space flight astronomy applications.

Introduction

We have recently begun a program for the development of intensified solid state array detectors for pulse counting ultraviolet astronomy applications. This effort has evolved from an ongoing program to provide efficient panoramic detectors for our rocket telescope-spectrometers for the measurement of the far UV spectral and imaging of a wide range of astronomical sources: planetary,[1,2] stellar,[2] and extragalactic.[3,4] These earlier detectors, all employing microchannel plates (MCP's) in the chevron configuration with resistive anodes for one or two dimensional imaging, while sufficient for the immediate application, demonstrated some undesirable characteristics; dynamic range limited to $\leq$ 1000 cts/sec, aliasing in the presence of strong spectral features, image drift, and resolution restricted to >.5%. These difficulties led us to investigate the concept of a high gain image converter coupled with a self-scanned solid state array and appropriate electronics for high speed photon event detection and location. Such a device would in principle have excellent image stability, considerably better resolution, and its independent pixels would eliminate aliasing and improve dynamic range. Furthermore, the intensifier package, once developed, could also be coupled with any of a wide range of visible light detector arrays currently available (and rapidly being developed) to suit a given application.

A number of detector systems utilizing this concept have been constructed in the past several years for ground based astronomy applications.[5,6,7] In order to produce sufficient gain for pulse counting, these designs have typically employed a multi-stage intensifier package with up to six electrostatic focus image tubes in tandem, or, more recently, straight-channel MCP intensifiers coupled with one or more electrostatic focus tubes.[6,8] These systems, while capable of photon counting at low rates with reasonable resolution, have characteristically poor pulse height distribution (PHD) resolution, non-uniform gain, and long phosphor decay tails at the output stage. These factors combine to make pulse counting difficult and limit the dynamic range by requiring successive frame subtraction and high threshold settings. They also suffer from relatively large size, distortion, and sensitivity to ambient electromagnetic fields, and require very high bias voltages, all of which make such a design impractical for space astronomy applications.

The recent development of high gain saturable microchannel plates (S.MCP's),[9] commercially available from Galileo Electro-Optics Corporation, has made possible an alternate intensifier approach. A single-stage intensifier for visible photon counting with a TV (Plumbicon) tube, which employs a curved channel MCP of a different type, has previously been described by Rossier, et al.[10] We have demonstrated that the single S.MCP in a proximity focussed intensifier tube produces more than sufficient gain for pulse counting

when fiber-optically coupled to a self-scanned photodiode array. This intensifier also exhibits a well-peaked PHD, very short phosphor decay time, uniform gain and, with a simple peak location algorithm for photon event location, demonstrates resolution limited by the S.MCP pore spacing. These qualities combined with its compactness, low bias voltage requirements (≲8KV), insensitivity to external magnetic fields and minimal distortion appear to make this intensifier design nearly ideal for use in space astronomy. The results, described below, of our initial testing of a prototype device have been sufficiently encouraging that we have adopted this detector concept for our Hopkins Ultraviolet Telescope (HUT) instrument - a .9 m telescope-spectrometer for spectrophotometry in the 900-1800 Å range,[11] scheduled for its initial flight aboard the Space Shuttle on OSS-3 in early 1985.

Description

The prototype detector system which we are currently testing consists of a custom-designed, vacuum flange-mounted image intensifier fiber-optically coupled to a self-scanning linear diode array with associated readout circuitry, an analog to digital converter, and an interface with a desktop computer. These components are described in detail below. The operation of the intensifier is illustrated schematically in figure 1.

The intensifier was constructed by ITT, Electro-Optical Products Division, from their standard 25 mm brazed ceramic tube components TIG welded to a 2-3/4 inch Varian Conflat flange which is suitably relieved. This flange mounting enables easy transfer of the device from processing hardware to testing facilities and allows for metal gasket high vacuum sealing onto the flight spectrometer where it is to be used in a windowless configuration.

The tube body supports a Galileo S.MCP 25 saturable microchannel plate (or 'C' plate - indicating the shape of the curved channels) with nominal 25 mm diameter active area and 25μ pores. The S.MCP produces $\sim 10^6$ electron gain in a single channel, thereby driving the channel into space-charge saturation, which results in a narrow pulse height distribution. The curved channel walls act to inhibit ion feedback which enables operation at high gain. Timothy[9] has tested these MCPs extensively and finds that, in order to take full advantage of their pulse saturating properties, the channel walls must be carefully cleaned by vacuum baking at 300° C followed by an electron scrubbing operation. Such a procedure was carried out on the MCP which we are testing although the plate was subjected to ambient air after the bakeout in order to process the photocathode in a separate facility at ITT.

The opaque CsI photocathode, highly efficient below 1800 Å, is evaporated directly onto the MCP input surface. Photoelectrons created on the surface are directed into a neighboring microchannel by a repelling field of ∿ 200 V/mm produced by a slotted baffle held negative with respect to the MCP input surface. The electrons exiting the MCP are proximity

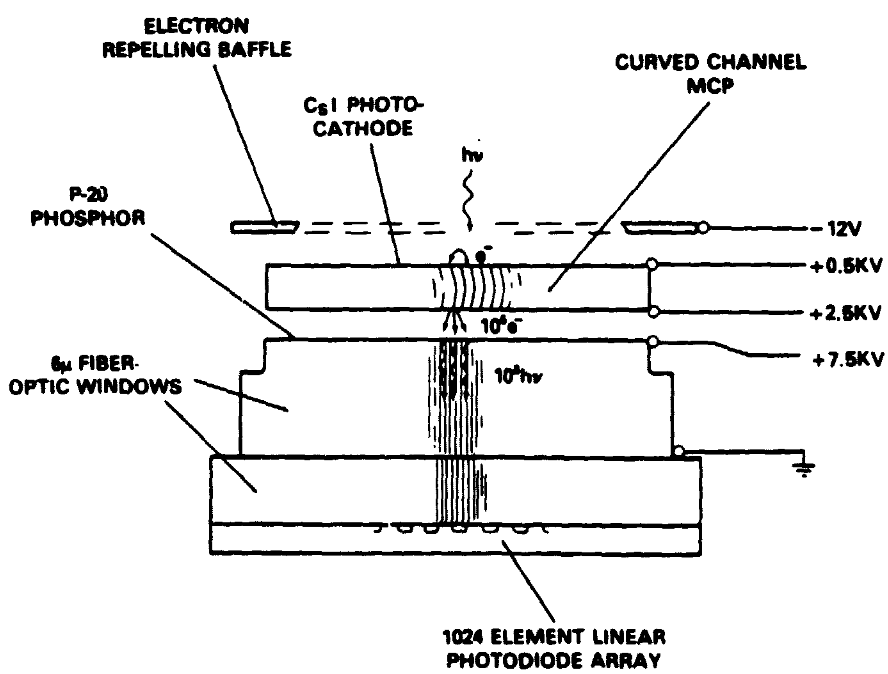

Figure 1. Detector Operation. This compact, single stage intensifier produces more than sufficient gain for photon counting with the Reticon diode array.

focussed across a .50 inch gap through a 5 KV nominal bias to the aluminum overcoated P-20 phosphor. The P-20 phosphor was chosen for its small grain size, hence good resolution, and its fast decay time and reasonably efficient coupling to a silicon photodiode array. The phosphor is coated onto a 6μ, 1:1, Galileo fiber optic output window with numerical aperture 1 and with extra mural absorber (EMA) to reduce resolution loss through its .520 inch thickness.

The tube body is potted in a cylindrical Delrin shell with Conothane EN-11, selected for its low outgassing properties. Four flying leads exit the potting shell radially to provide high voltage electrical connections to the electron repelling baffle, the MCP input and output surfaces and the phosphor. The windowless intensifier is approximately 1 inch thick. A MgF_2 window, mounted in a mating flange, is attached to the front of the intensifier for laboratory testing. A 0.2 ℓ/s ion pump is also welded into this flange to keep the tube pressure low as the MCP cleans up.

The Reticon RL1024SF linear photodiode array was chosen because of its format, which is ideally matched to the HUT f/2 Rowland spectrometer. The 25 μ-wide diodes approximate the resolution of the spectrometer and their 2.5 mm height allows for the astigmatism produced by such a fast spectrometer design. This array is also conveniently provided with a 6μ fiber optic input window which allows for easy coupling to the intensifier. For our initial lab testing, the array is read out by the Reticon evaluation circuit board modified to provide a crystal-controlled clock. The combined odd- and even-diode video stream is digitized to 6 bits accuracy; the 4 most significant bits are then multiplexed into 16 bit words which are accepted by an HP 9845B desktop computer via a bit-parallel DMA port. A synch word is provided to flag the end of each scan. This scheme, while readily implemented, allows us to scan the array at only 250 KHz (5 ms frame time), due to the slow amplifier response of the readout circuit and the DMA rate of the HP 9845. A new readout circuit which should enable operation of the array at up to 2 MHz with good dynamic range, has been designed and fabricated. A computer interface which employs a large FIFO buffer register, preceded by a hardware threshold discriminator, is being designed. These will enable high speed testing of the detector in the near future.

A software package has been developed to evaluate the detector performance and to develop the most efficient algorithms for pulse counting and event location. Code was written for measurement of the pulse height distribution, the pulse shape and width, and for plotting the raw scan data, etc. These routines, implemented primarily in BASIC, operate very slowly on the HP 9845. Thus the data is not analyzed in real time but a 'shot' of data is transferred to the memory (typically 124 detector scans), stored on tape, and then analyzed. Recording of the raw data permits direct comparison of the results of processing the same data set with different event location algorithms.

Our initial approach to the photon event location task was to simply select the diode with peak signal in each pulse and, if its amplitude lies within a discriminator window, increment the appropriate histogram bin by one count. This code was implemented in assembly language for more rapid data processing. Subsequently, more complex pulse location algorithms have been developed which evaluate the centroid of acceptable pulses and bins the results into 2048 pixels (of 1/2 diode width). We are also examining algorithms which eliminate sensitivity to differences in the odd- and even-diode readout channels. The ultimate goal of this program is to determine the simplest, fastest-running algorithm which locates the pulses to sufficient accuracy that the detector resolution is limited by the intensifier. A hardware and bit-slice microprocessor-based data processing circuit is under construction for spaceflight applications where downlink telemetry bandwidth requires real time data reduction to the spectral histogram; the anticipated processing capacity is 10^4 cts s^{-1}.

Performance characteristics

The prototype detector system is being tested on an optical bench equipped such that a pinhole or slit, illuminated by a mercury pen lamp, may be imaged onto the detector. The CsI photocathode has sufficient response at the Hg resonance lines, λ1849 and λ2537 Å, that adequate count rates are easily achieved. The detector may also be diffusely illuminated for 'flat field' measurements by means of an Hg lamp and pinhole arrangement located several meters in front of the photocathode.

Intensifier performance

The well-peaked PHD characteristic of the S.MCP is shown in figure 2. The measurement was made with the detector diffusely illuminated, and with 1.9 KV MCP bias and 4.1 KV phosphor bias. The PHD resolution, defined as the full width half maximum gain variation divided by the modal gain, is approximately 70%. The PHD resolution is essentially independent of the phosphor bias and position along the array. The modal gain was found to vary less than 30% across the length of the array. While the well-defined PHD peak and gain

uniformity demonstrated here combine to ensure the high-efficiency photon counting capability of the detector, it appears that the PHD resolution may readily be improved by careful S.MCP selection and more extensive channel scrubbing. Timothy[9] has achieved PHD resolutions as low as 34% with these plates. He has also life tested one S.MCP to an accumulated dose of $>10^{11}$ pulses mm^{-2} and found that it maintained its high gain.

With a 4.1 KV phosphor bias, pulses in the center of our PHD produced peak diode signals of ~3% of saturation, which corresponds to $\sim 2.5 \times 10^6$ electrons. Assuming 50% total coupling losses, 60% diode QE at the 5600 Å wavelength of the P-20 phosphor and noting that ~20% of the pulse signal occurs in the peak diode, we calculate that $\sim 4 \times 10^7$ photons are emitted by the phosphor. This corresponds to a phosphor conversion efficiency of ~.015 ph eV^{-1}, since the MCP gain is $\sim 1 \times 10^6$. Although the intensifier produces more than sufficient gain when operated at 4.1 KV phosphor bias, the gain may be increased by a factor of 2 by operating at 5 KV, or by a factor of ~3.5 at the rated 6 KV.

An 'average' pulse shape is illustrated in figure 3. This histogram was calculated by registering the peaks of pulses, uniformly distributed over the length of the array, adding the signal in each of the 8 diodes on both sides of the peak, and normalizing. The FWHM of this approximately Gaussian shape is about 100μ, or four diode widths, and virtually all of the signal is confined to within 10 adjacent diodes. While the result compares favorably with previous multi-stage intensified Reticon detectors, the pulses are broader than expected from a single stage MCP intensifier. We have measured the spot diameter produced by a standard ITT 18 mm straight channel MCP intensifier with P-20 phosphor, operated at $\sim 10^3$ electron gain, to be ~55μ FWHM. Two mechanisms have been proposed which may be operating to broaden the pulses: poor collimation of the electron pulse exiting the S.MCP due to its very shallow (~.5 channel diameter) end spoiling (most likely the dominant effect), and spreading of the high current-density electron pulse at the phosphor. There is no apparent reason why the S.MCPs cannot be end spoiled to a greater depth; we are currently pursuing this with Galileo. A process known as intagliation, whereby the cores of the fiber optic are partially etched out before application of the phosphor, which may serve to localize the pulses, is being investigated by ITT.[12] However, this technique is evidently still in an experimental stage and appears to suffer from difficulties in getting the phosphor grains to reside in the intagliated wells.

The pulse decay time of the P-20 phosphor was measured by displaying the output signal of a photomultiplier tube directly on a storage oscilloscope. The pulses decay to 10% of their peak within ~10μs. Rosier[10] has measured a somewhat larger decay time of 30 μs (to the 10% of peak level) for a similar intensifier operated at lower ($\sim 10^5$) gain. This very short decay time is attributed to the high instantaneous current density of the electron pulses, which is on the order of several amps cm^{-2}. This short pulse duration enables very rapid scanning of the array without the danger of counting a single pulse twice, on successive frames, and therefore also precludes the need for successive frame subtraction - required by the long decay tails produced by multi-stage intensifier packages.

We have not yet measured the quantum efficiency (Q.E.) of the detector system. However, our most recently constructed resistive anode encoded detector, which also employs a CsI

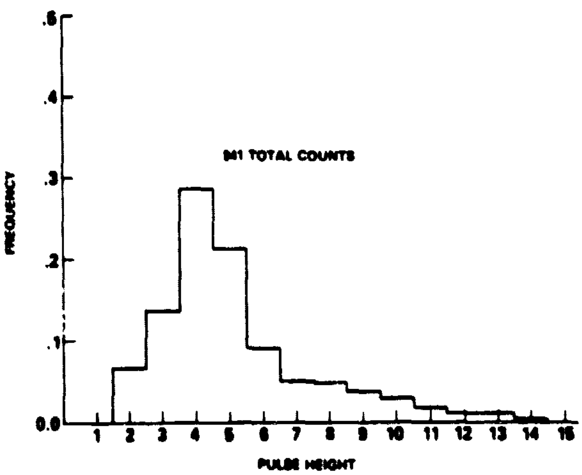

Figure 2. Pulse Height Distribution. The PHD resolution (~70%) demonstrated by the detector enables efficient photon counting.

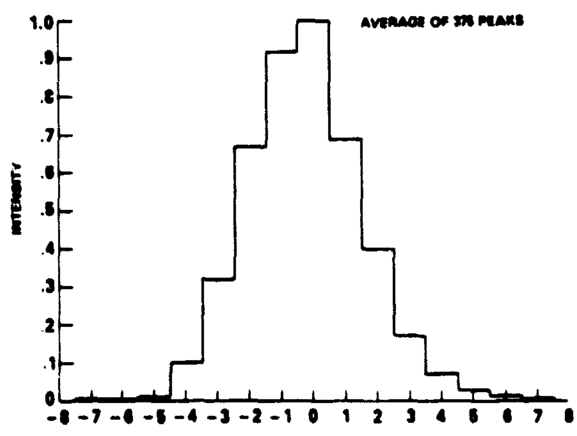

Figure 3. 'Average' Pulse Profile. The approximately Gaussian shape of the video pulses produced by each photon event has ~100μ FWHM.

photocathode deposited directly on the MCP, yielded 34% Q.E. at Lyman α. The better PHD resolution of the S.MCP device should serve to improve this efficiency. A Q.E. of 48% at Lα ... a CsI coated S.MCP detector system has been reported by Timothy.[13]

Resolution.

The spatial resolution of the detector system was evaluated initially with the simple peak detecting algorithm for pulse location described above. The profile obtained by imaging a 22μ spot on the photocathode is shown in figure 4 (dashed profile) which illustrates that this simple algorithm can locate the centers of the pulses to within the 25μ diode width. The resolution is further improved by rejecting ~7% of the pulses, which are wider than normal or which occur in close proximity to another pulse, as is indicated by the solid profile. Figure 5 shows the approximately 50μ FWHM profile obtained for a 1.5 mm tall by 22μ wide slit image, with the long dimension of the slit carefully aligned with the diodes.

In both of these cases the actual detector resolution (minimum 2 pixels) is limited or degraded by the 25 μ pixel width, and considerable information concerning the center of an event is discarded upon selecting only the peak diode. A more careful (but necessarily much slower to implement) calculation of the pulse centroid can yield the pulse location to within a small fraction of a diode width. The centroid is given simply by:

$$x = \frac{\Sigma_n n \cdot S_n}{\Sigma_n S_n}$$

where n is the diode number and S_n is the signal on diode n. We have calculated that for 100μ FWHM Gaussian-shaped pulses convolved with the trapezoidal aperture response of the diode array and digitized to 4 bits accuracy, the maximum error in position determination by a centroid calculation over 9 diodes centered on the pulse is ~25% of the diode width (see below). The ultimate resolution-limiting factor then is not the diode spacing, but the MCP pore spacing. (Note that because the pores are spaced in a hexagonal close-packed pattern the contribution from the pore spacing to the resolution of properly aligned slit images can be smaller than the spacing, if the pattern is coherent over the length of the image.) A 9-point centroiding algorithm which bins the counts into 2048, ½ diode-wide pixels was used to again measure the profile of the 22μ slit image (figure 6). The ~40μ (FWHM)

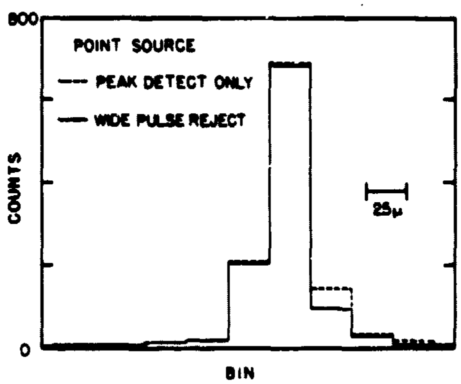

Figure 4. Point Source Image Profiles. These profiles were obtained by imaging a 22μ diameter spot and locating photon events with simple peak signal detection algorithms. Pixels are 25μ wide.

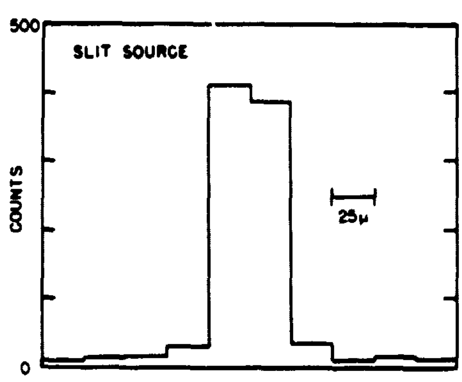

Figure 5. Slit Image Profile. A 1.5 mm tall x 22μ slit was imaged onto the detector and a peak detection algorithm was used for event location. Pixels are 25μ wide.

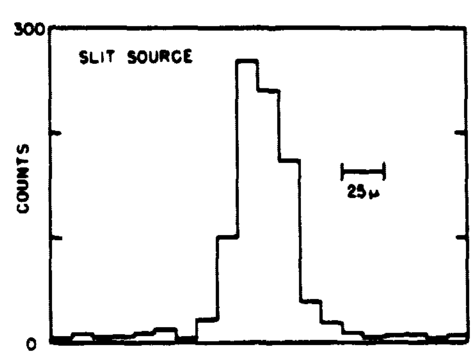

Figure 6. Centroided Slit Image Profile. Photon events were located to ½ diode-width accuracy with a pulse centroiding algorithm operating on the same raw data used for Figure 5. Pixel width is 12.5μ

resolution of this profile is nearly all attributable to the MCP channel spacing and the slit image width, and clearly shows the advantage of centroiding into narrower pixels.

Fixed-pattern noise.

A fairly large amount of odd-even fixed pattern noise was very evident in the first 'flat field' images that we produced, using the peak-detect algorithm. This is associated with the separate odd and even video lines which, on the Reticon readout circuit board, are independently amplified and subsequently recombined. Small offsets, corresponding to ~25% of our least significant bit (LSB) level, between these amplifiers produced very noticeable (30%) odd-even asymmetry in the histogram. Furthermore, the offset is found to drift wildly during electronics warm-up, and could not be trimmed out over the entire length of the array. While use of temperature stable components in our newly constructed readout circuitry should minimize the drift; it will probably be impossible to reduce the offset over the entire array to a level at which no significant fixed pattern is discernable. Correction for the offset cannot be made prior to peak location in the dedicated pulse processing computer, since the offset required to produce significant odd-even asymmetry is a small fraction of the LSB level. Fortunately, the nine point centroid calculation algorithm was found to be much less sensitive to this offset: flat field histograms which show ~50% asymmetry (defined as the difference in counts accrued in alternate bins divided by the sum) when produced by the peak location algorithm, show only 10% asymmetry when centroid calculation is used.

Summary and discussion

The single stage intensified Reticon device which we have described here has demonstrated its feasibility as a photon counting detector and clearly holds promise for UV space astronomy applications. The 40μ resolution, and stable, rigid mechanical image registration, together with the independent diode property which allows photometric accuracy to be maintained over the remainder of the spectrum when bright saturating features are present, combine to make the detector an obvious improvement on the resistive anode MCP devices which we have been using. In addition, its small physical size, insensitivity to external fields, and low bias voltage requirements make this intensifier design desirable for both space flight instruments and, with modifications for use of a semi-transparent photocathode proximity focussed on the S.MCP, for ground based applications.

As mentioned above, we are investigating improvement of the detector performance characteristics, in particular, reduction of the pulse image width, improvement of PHD resolution, minimization of odd-even fixed pattern noise, increase of the array scan frequency, and identification of the most desirable pulse locating algorithm. Narrowing the pulse width is important for two reasons: pulse overlapping occurs at a lower rate for narrow pulses thereby improving the dynamic range, and accuracy and speed of the centroiding algorithm is also improved as fewer pixels are involved. We believe that with proper end-spoiling of the S.MCP a substantial reduction of the pulse width, perhaps to ~60μ, will be achieved.

We have investigated the accuracy of the event location algorithm as a function of pulse width, digitization accuracy, and the diode interval over which the pulse centroid is calculated. The pulses were assumed to be Gaussian in shape, and were convolved with the trapezoidal aperture response of the Reticon diode array to compute the error produced by calculating the centroid over both 5- and 9-diode intervals centered on the diode with peak signal. Some of the results are presented in figure 7. The curves represent the pulse location error, as a fraction of the diode width, versus the true pulse center as it is moved in 32 equal steps from the center to one edge of a diode; errors for the pulse locations on the other side of the diode center are the symmetrical inversion of those shown. In each case the pulse peak signal is one half of full scale of the ADC. Although the detailed shape of each curve depends strongly on the pulse amplitude, the maximum and RMS error are relatively insensitive to the pulse size, so these curves may be taken as representative. The solid curve illustrates the accuracy achieved for the conditions with which the line profile presented in figure 6 was measured: pulse width, W = 4 diodes, ADC accuracy = 4 bits, and using a 9 point centroid calculation. The rapid changes in error with small position shifts are due to the relatively poor digitization accuracy. The error can be much reduced by using a 6 bit ADC as is illustrated in the dashed curve, but only at the expense of reducing the speed of the event location calculation. The centroiding time may be markedly reduced by calculating the centroid over a smaller diode interval but large errors result if the wings of the pulse profile are ignored as shown in the dot-dash curve which limits the calculation to a 5-diode interval. Clearly it is most desirable to reduce the pulse width in order to improve both speed and accuracy of the centroid computation. If the width can be narrowed to 2.5 diode widths then the relatively fast 4 bit, 5 point calculation will suffice, as is demonstrated by the ≤12% diode-width pulse location errors of the dotted curve.

The ultimate resolution limiting factor, however, is the S.MCP pore spacing. Fortunately,

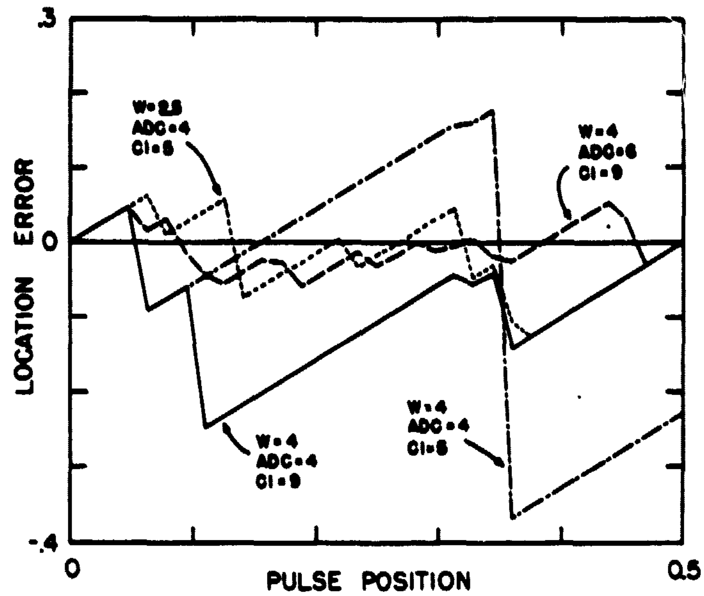

Figure 7. Pulse location error vs. pulse location. These curves illustrate the effects of pulse width (W, diode widths), digitization accuracy (ADC, bits), and centroiding interval (CI, diodes) on event location accuracy.

Galileo Electro-Optics Corp. is now marketing a 12μ pore S.MCP with 15μ center-to-center spacing; we will evaluate one of these plates in the near future. Preliminary indications are that the PHD resolution achieved with the 12μ S.MCP is somewhat poorer (∿70%) than that of the 25μ version, but should still readily permit efficient pulse counting. They also operate at about half the gain of the 25μ plates; again, this should pose no problem since the intensifier tested provided more than sufficient gain even at low (4.1 KV) phosphor bias. A detector system employing a 12μ S.MCP and pulse centroiding to ¼ diode accuracy might be expected to yield ∿25μ resolution.

We are now beginning to test a custom-designed array readout module which has been carefully laid out and employs only the high-reliability, temperature-stable components required for space flight qualification. It is our hope that this circuit will allow us to trim out most of the odd-even video offset in a stable manner although variations of the offset over the length of the array will prevent its complete eradication. The module will also allow scan rates to 2 MHz, with sufficient dynamic range, and will digitize the video signal to 6 bits accuracy. We are concurrently designing a real time data processor based on the AMD 2900 series bit-slice microprocessor hardware. Preliminary estimates indicate that this device will be able to calculate pulse centroids and increment a histogram for about 10,000 counts s^{-1}. We chose a fast microprocessor approach to the pulse location task, as opposed to a circuit implemented purely in hardware, in order to maintain as much flexibility as possible in the location algorithm. While firmware code alterations are nontrivial, such changes are much more readily made when compared to circuit redesign and fabrication, especially for the high quality electronics required for space flight.

We believe that this detector has sufficient merit that we plan to use it with a prototype version of the HUT spectrometer, to measure the FUV (λ850-1750 Å) daytime airglow spectrum aboard an Aerobee sounding rocket in the near future. A second intensifier, with minor modifications from the one described here, is being built for this purpose. The sounding rocket flight of the detector, if successful, will then serve as a means to qualify it for use on the HUT shuttle instrument.

Acknowledgments

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